The behavioral effects of index insurance in fisheries

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Fisheries are vulnerable to environmental shocks that impact stock health and fisher income. Index insurance is a promising financial tool to protect fishers from environmental risk. However, insurance will change fisher's behavior through moral hazards. We provide the first theoretical application of index insurance on fisher's behavior change to predict if index insurance will incentivize higher or lower harvests in unconstrained settings. The direction of harvest changes depends primarily on: the ability for fishers to mitigate production risk, the correlation between sources of risk, and the type of risk protected by the insurance contract. Simulating from parameters estimated for four Norwegian fisheries shows index insurance could increase harvest by a median of 15% or decrease harvest by 4%. Before widespread adoption, careful consideration must be given to how index insurance will incentivize or disincentivize overfishing.

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1 Introduction

Fishing is a vital economic engine to coastal communities and is the primary source of protein for millions of people (Sumaila *et al.* 2012; Teh and Sumaila 2013; FAO 2020). Supporting these communities requires protection from enormous degrees of environmental risk. Environmental fluctuations directly impact fishers of all scales from large industrial vessels to small scale subsistence fishers.

Marine heatwaves provide a clear example of how environmental variability impacts fishery biological and economic productivity. Marine heatwaves increase animal thermal stress diminishing reproductive ability (Barbeaux *et al.* 2020), stunting growth (Pandori and Sorte 2019), pushing species outside their usual habitats (Cavole *et al.* 2016), and may directly increase mortality (Smith *et al.* 2023). Expanding fish habitat ranges increase costs when moving beyond the fishing grounds of established ports (Rogers *et al.* 2019). The variability from marine heatwaves alone impacts 77% of species within economic exclusion zones and reduces maximum catch potential by 6% (Cheung *et al.* 2021). Marine heatwaves are often accompanied by harmful algal blooms and diseases leading to additional fishery collapses (Oken *et al.* 2021).

Weather can also impact fisher harvesting efficiency beyond influencing the health of the underlying stock. Rolling seas and high wind speeds make it more difficult to harvest (Alvarez *et al.* 2006) in addition to raising the danger to crew and vessel (Heck *et al.* 2021). More intense storms threaten coastal infrastructure vital to fishing communities (Sainsbury *et al.* 2019). Fishers actively avoid fishing in destructive weather at the expense of lost income (Pfeiffer 2020).

Individual choices by fishers and fishery management mitigate environmental risk. Fishers are highly sensitive to risk, especially income risk, and demonstrate risk aversion despite working a seemingly risky profession (Smith and Wilen 2005; Holland 2008; Sethi 2010). Individual efforts to mitigate risk such as choosing consistent, known fishing grounds over risking exploring unknown spots (Holland 2008) or choosing to fish less after storms and hurricanes (Pfeiffer 2020; Pfeiffer *et al.* 2022) are likely to be incomplete and that financial tools such as insurance could further help fishers. However, there is a lack of financial tools available to fishers to address income risk as a result of environmental fluctuations (Sethi 2010; Kasperski and Holland 2013). There is growing interest in developing new financial tools to alleviate financial and income risk for coastal communities (Wabnitz and Blasiak 2019; Sumaila *et al.* 2020).

Insurance may be an ideal financial tool for risk management in fisheries as it is scalable, protects against environmental shocks, and smooths income for fishers (Watson *et al.* 2023). Currently, insurance in fisheries is primarily used to protect assets such as vessel hulls or fishing gear (FAO 2022). Insurance coverage could be expanded to include income variability originating from weather and biological productivity shocks. An insurance product covering these environmental risks could improve fisher welfare and promote community resilience (Maltby *et al.* 2023).

Policy makers have begun advocating for new fisheries insurance programs modeled after agricultural crop insurance programs (Murkowski 2022). Index insurance is one such product extolled by practitioners as a prime candidate for fisheries productivity insurance (Watson *et al.* 2023). Index insurance gained traction in agriculture as an effective alternative to traditional crop insurance in developing countries because it had lower administrative cost, minimized moral hazards, and does not require claim verification (Collier *et al.* 2009; Carter *et al.* 2017). Whereas indemnity crop insurance requires an assessment of loss to an individual, index insurance uses an independent measure as the basis for issuing payouts to all policyholders. The difficulty in establishing individual indemnified loss for individuals in fisheries is a key reason for index insurance has risen in prominence (Herrmann *et al.* 2004; Watson *et al.* 2023).

An example pilot program through the Caribbean Oceans and Aqaculture Sustainability Facility (COAST) uses index insurance to payout a set amount to fishers when indices of wave height, wind speed, and storm surge indicate a hurricane (Sainsbury *et al.* 2019). Triggers are the index values that initiate a payout. Contract design revolve around establishing suitable triggers to cover environmental loss.

One crucial area that remains under studied is the potential influence of insurance on fishers behavior. Moral hazards are decisions by insured agents that they would not otherwise take if they were uninsured (Wu *et al.* 2020). Currently, the operational assumption of practitioners appears to be that index insurance would completely avoid any moral hazards in fisheries and intrinsically motivate greater fishery sustainability (RARE 2021). Yet, there are two components to insurance moral hazard: "chasing the trigger" and "risk reduction". "Chasing the trigger" is the directed behavior of policyholders to increase the likelihood of a payout. For example, a fisher actively choosing to fish less to receive an indemnified harvest insurance payment. Index insurance completely eliminates this moral hazard through the independent and uninfluenced index (fishers cannot affect sea surface temperature). "Risk reduction" occurs through possessing an insurance contract that protects policyholders from risk. Policyholders may reoptimize their decisions once protected from risk. Index insurance remains susceptible to this element of moral hazard that could manifest in maladaptive behaviors. In fisheries, it could be choosing to fish more when insurance covers losses. All preliminary analyses of fisheries index insurance are missing rigorous assessment of this element of moral hazards.

Previous studies in agriculture provide compelling evidence that behavior change ought to be expected in fisheries. Index insurance applied to grazing in pasture commons shows clear evidence of risk reduction moral hazards leading to environmental degradation (Müller *et al.* 2011; Bulte and Haagsma 2021). Other studies from agriculture describe a more equivocal relationship between insurance and environmental sustainability. The impact of insurance on environmental sustainability depends on the underlying risk reducing or increasing qualities of inputs used in production (Ramaswami 1993; Mahul 2001; Mishra *et al.* 2005). Risk increasing inputs will always lead to increased input use with insurance, while risk decreasing inputs will always lead to decreased input use with insurance. Numerous agricultural studies confirm insurance incentivizes changes in inputs (Horowitz and Lichtenberg 1993; Babcock and Hennessy 1996; Smith and Goodwin 1996; Goodwin *et al.* 2004; Mishra *et al.* 2005; Cai 2016; Deryugina and Konar 2017; Claassen *et al.* 2017; Elabed and Carter 2018; Sibiko and Qaim 2020; Stoeffler *et al.* 2022).

Fisheries differ from agriculture in crucial ways, which gives merit to analyzing the behavioral effects of index insurance in this new setting. Previous studies articulated hypothetical examples of moral hazards in fishery indemnity insurance programs, such as encouraging fishers to fish in foul weather or to not exit the fishery after a bad year of harvest (Herrmann *et al.* 2004; Watson *et al.* 2023). However, neither study built testable models to uncover moral hazard impacts on fisheries. This paper is the first to build a theoretical framework that will better predict the long term sustainability of index insurance programs in fisheries.

Stock abundance is a necessary input in fisheries production, and is a major source of production uncertainty. Fishers will always face biological risks because of the stochastic nature of fish growth. However, fishers can also face production risk from weather shocks that do not directly impact the stock of fish. For example, storms do not impact the underlying stock of fish, but greatly increase the production risk of fishers. Fishers may not be able to influence the variance of stock abundance, but they do make choices to limit other forms of risks. We present a new model that introduces both biological and production risk in fisheries to better accommodate existing individual fisher risk mitigation strategies. With an adaptive, more flexible specification of production, we test how index insurance will incentivize behavior change in fisheries with multiple sources of risk.

The remainder of the paper structured as follows. Section 2 details a new stochastic production function for fisheries that integrates both biological and production risk. Section 3 proves that index insurance will change fisher behavior, but the outcomes are ambiguous and depend on the risk effects of inputs and the interaction between shocks. Section 4 extends the theoretical model to account for multiple inputs in fishing that reflects the decisions of fishers in the empirical setting. Section 5 numerically estimates potential harvest changes with an index insurance program. Parameters are calibrated with an application to Norwegian fisheries through the results of Asche *et al.* (2020). Section 6 concludes with a discussion on the suitability of fishery index insurance. Fishery index insurance ultimately has ambiguous effects on fisher behavior. Before widespread adoption, careful consideration must be given to how insurance will incentivize or disincentivize overfishing.

2 Risky Production in Fisheries

We define a novel fishery stochastic production model with two sources of variability. Our model extends traditional fishery production models that only account for biological risk to include an additional source of uncertainty that affects fisher production. Fishers are now able to make risk decisions along more than one margin, which better reflects the complexity of fisher decisions and risk mitigation abilities.

Fishers use a vector of m inputs $X \in \{x_1, x_2, ...x_m\}$ in a harvest technology function $f(X)$ that interacts with a stochastic stock of fish, $\tilde{B}$. The stock of fish can be separated into a mean component $\hat{B}$ that fishers expect given factors such as prior year escapement, and a variance component θ. This formulation is often referred to as process error, where randomness could originate from weather shocks in the current period or measurement error (Tilman *et al.* 2018; Merino *et al.* 2022). Greater realizations of biomass lead to corresponding increases in production. The variance component θ can have any distribution so long as $\mathbb{E}[\theta] = 0$. Weather variables typically associated with biological productivity such as sea surface temperature, upwelling, or primary production are good representations of what θ could capture.

However, fishers are also exposed to other forms of risk beyond biological risk. Weather shocks, regulatory changes, and spatial variation all impact fisher production. All other forms of risk not captured by biological risk are production risk, ω. Fisher inputs may interact with these risks through the risk effect function $h(X)$. Total fisher production, y, is defined by these two sources of stochasticity and harvest technology (Equation 1).

$$y = f(X)\hat{B} + \theta f(X) + \omega h(X) \tag{1}$$

Equation 1 is a general form of fishery production that separates the productivity risk effects of inputs from the biological risk. The biological risk is captured by $\theta f(X)$. Harvest technology $f(X)$ is always a concave function, $f_x(X) > 0, f_{xx}(X) < 0$. Cobb-Douglas or linear harvest from Gordon-Schaefer are excellent examples of $f(X)$.

The risk effects of inputs are captured by $\omega h(X)$, where $h(X)$ can either contribute to risk or decrease it, $h_x(X) \lesseqgtr 0$. Fishers make decisions that mitigate some level of production risk (Holland 2008). Fishers have the ability to influence the degree of risk exposure through technical expertise and the skill of captains that limit "luck" in fishing (Kirkley and Strand 1998; Kompas *et al.* 2004; Alvarez *et al.* 2006). $h(X)$ allows for the inclusion of these risk mitigation strategies in production. Inputs that lower risk will have $h_x(X) < 0$ and are called risk decreasing, while inputs that increase risk will have $h_x(X) > 0$ and are called risk increasing in line with Just-Pope Production functions of agriculture (Just and Pope 1978)[1].

Empirical testing in two case studies indicate the existence of these risk effect margins and that fishers use them while making input decisions. Eggert and Tveteras (2004) modeled the

[1]Observe that $f(X)$ is always risk increasing by it's concave definition $f_x(X) < 0$

Swedish trawler fleet's gear choices with production risk effects, and found that fishers account for both the expected revenue and the variance of revenue when choosing what type of gear to deploy. They do not provide explicit estimates of which gear is risk increasing or decreasing, but the results suggest that fishers are sensitive to the risk effects of gear.

Asche *et al.* (2020) provides the only known estimate of the risk effects of inputs in fisheries. Fishery inputs possess both risk increasing and decreasing qualities that change depending on the exact nature of the fishery. We will use their empirical findings later in Section 5 to estimate the potential impacts of index insurance on fishery production. Their results indicate that the same inputs have different effects on the average and the variance of harvest, $h(X) \neq f(X)$, but also inputs may actively reduce variance and risk through $h_x(X) < 0$.

Our new stochastic production function introduces a more flexible risk structure while maintaining the biological risk crucial to fishery production. Management is the remaining unique feature of fishery production not explored in this paper. We want to analyze the interaction of insurance on fisher behavior in unconstrained settings first to derive a clearer incentive structure. Adjustments to harvest through management would first have to overcome the fundamental incentivizes analyzed in the next section. We examine these conditions by building a utility maximization problem for fishers with insurance and the new stochastic production function.

3 Index insurance in fisheries

Fishers derive utility from profits and are often price takers, so we add a convex cost function to Equation 1 and normalize price of harvest to 1.

$$\pi = f(X)\hat{B} + \theta f(X) + \omega h(X) - c(X) \tag{2}$$

The existence of two sources of risk allow for an insurance contract to be built to protect against either source. We assess the potential behavior implications of using an insurance contract to protect against biological, θ, or production risk, ω. Insurance companies have perfect information on both distributions in our model. In reality, insurance agents may only have sufficient information on one of the risks to form a suitable contract. For example, biological shocks may be easier to observe and monitor compared to individual production shocks. Insurance companies would then build contracts based on realizations of θ instead of ω.

To most seamlessly integrate index insurance, we create insurance lotteries by defining a trigger, $\bar{z}$, where $z \in \{\theta, \omega\}$. Insurance pays out a constant amount γ if $z < \bar{z}$. The separation of two random variables introduces basis risk into insurance contracts as a contract triggered solely on ω can not protect against all the biological risk of θ. No prior study has examined basis risk on the optimal input use before, but it is well known to change the optimal amount of insurance coverage in agriculture (Clarke 2016; Lichtenberg and Iglesias 2022). Therefore, we leave it as a feature, but will have to impose stronger conditions to achieve some tractable analytical results. During the numerical simulations, we can test the effects of basis risk more clearly.

Actuarilly fair insurance allows the premium, ρ, paid in both lotteries to be the probability of receiving a payout times the payout amount, $\rho = J(\bar{z})\gamma$, where $J(z)$ is the cumulative distribution of the representative shock. Additionally, if we set the trigger to $\bar{z} = 0$ to indicate any time weather negatively impacts total production, profits will enter corresponding bad and good states. This leads to the following two lemmas:

Lemma 3.1. *When shocks are uncorrelated, for a specific input* x_m*,*

$\frac{\mathbb{E}[\partial\pi|z<\bar{z}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|z>\bar{z}]}{\partial x_m} > 0$ *if* $h_{x_m}(X) < 0$ *and* $z \equiv \omega$.

Otherwise, $\frac{\mathbb{E}[\partial\pi|z<\bar{z}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|z>\bar{z}]}{\partial x_m} < 0$ *if* $h_{x_m}(X) > 0$ *or* $z \equiv \theta$.

Lemma 3.2. *When shocks are perfectly correlated, for a specific input* x_m*,*

$\frac{\mathbb{E}[\partial\pi|z<\bar{z}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|z>\bar{z}]}{\partial x_m} < 0$ *if* $h_{x_m}(X) > 0$

And, $\frac{\mathbb{E}[\partial\pi|z<\bar{z}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|z>\bar{z}]}{\partial x_m} \lesseqgtr 0$ *if* $h_{x_m}(X) < 0$.

The proofs of Lemma 3.1 and Lemma 3.2 are included in the appendix. In plain words, Lemma 3.1 says that risk decreasing inputs are more profitably in bad states of the world compared to good states, and that it matters which index determines the bad state. Lemma 3.2 indicates that perfectly correlated shocks lead to ambiguous expected marginal productivity if inputs are risk decreasing regardless of which index determines the state. Risk increasing inputs will always lead to greater expected marginal profit in good states. These lemmas are instrumental in later proofs.

Risk aversion is a necessary condition for insurance to be desirable (Outreville 2014). Therefore, we assume fishers are risk averse to income shocks through a concave utility function. Fishers will maximize their own expected utility across lotteries by selecting inputs with an exogenous insurance contract (Equation 3). We use z_i to indicate the index that insurance indemnifies and z_r as the other variable that influences catch. The choice of insurance contract only modifies the bounds of the integral and the differential variable.

$$U \equiv \max_X \mathbb{E}[U] = \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta) u(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{z}_i))\gamma) dz_i + \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta) u(\pi(X, \hat{B}, \theta, \omega) - J(\bar{z}_i)\gamma) dz_i \Bigg] dz_r \tag{3}$$

The general model in Equation 3 is a flexible framework that can be applied to any fishery production model. Basis risk is captured by the joint distribution $j_{\omega,\theta}(\omega,\theta)$. Fishers will make inputs decisions on the distributions of both ω and θ to maximize their expected utility.

We first examine the effects of index insurance on optimal input decisions for one input, $X \in \{x\}$. The first order condition that solves Equation 3 is then:

$$\begin{aligned}\frac{\partial U}{\partial x} &= \int_{-\infty}^{\infty}\left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)u_x(\pi(x,\hat{B},\theta,\omega)+(1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)dz_i\right. \\ &\quad \left. + \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)u_x(\pi(x,\hat{B},\theta,\omega)-J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)dz_i\right] dz_r \\ &= 0\end{aligned} \tag{4}$$

To find the impact of insurance on optimal input, we use the implicit function theorem on the first order conditions.

$$\frac{\partial x^*}{\partial \gamma} = -\frac{\frac{\partial U}{\partial x \partial \gamma}}{\frac{\partial^2 U}{\partial x^2}}$$

By the sufficient condition of a maximization problem, $\frac{\partial^2 U}{\partial x^2}$ is negative so we can focus solely on the numerator to sign the impact of insurance on optimal individual input.

Differentiate equation Equation 4 with respect to insurance.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty}&\left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)u''(\pi(x,\hat{B},\theta,\omega)+(1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{z}_i))dz_i\right. \\ &\left. + \int_{\bar{z}_r}^{\infty} j_{\omega,\theta}(\omega,\theta)u''(\pi(x,\hat{B},\theta,\omega)-J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{z}_i))dz_i\right] dz_r\end{aligned} \tag{5}$$

Insurance will lower utility variance regardless of which index the contract is structured on. We examine the input decisions of insurance contingent on the source of risk the insurance is designed to protect. First we examine the uncorrelated case to isolate insurance effects more clearly.

Proposition 3.1. *For feasible index insurance contracts specified at trigger $\bar{\omega} = 0$, when ω and θ are independent random variables, optimal fisher input will decrease when $h_x(x) < 0$ and increase when $h_x(x) > 0$.*

For feasible index insurance contracts specified at trigger $\bar{\theta} = 0$, when ω and θ are independent random variables, optimal fisher input will always increase.

Proof. We focus on an index of ω first. The steps to solve for a θ index are nearly identical.

Independence of ω and θ allows us to factor out the joint distribution in the integral of Equation 5 into the respective marginal distributions.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} j_\theta(\theta) \Bigg[&\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) u''(\pi(x, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega)(1 - J(\bar{\omega})) d\omega \\ &+ \int_{\bar{\omega}}^{\infty} j_\omega(\omega) u''(\pi(x, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega)(-J(\bar{\omega})) d\omega \Bigg] d\theta\end{aligned} \tag{6}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 6.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} &j_\theta(\theta) J(\bar{\omega})(1 - J(\bar{\omega})) u''(\theta, \cdot) \\ &\left[\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\omega - \int_{\bar{\omega}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\omega \right] d\theta\end{aligned} \tag{7}$$

The first term outside the brackets is negative by the definition of concave utility, $u'' < 0$. Lemma 3.1 demonstrates the interior of the brackets is positive when $h_x(x) < 0$ as the marginal profit in the bad state is greater than the marginal profit in the good. Therefore, index insurance will decrease input use for risk decreasing inputs when the shocks protected by insurance can be ameliorated through inputs and are independent of biological shocks.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} &\overbrace{j_\theta(\theta) J(\bar{\omega})(1 - J(\bar{\omega})) u''(\theta, \cdot)}^{-} \\ &\left[\underbrace{\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\omega - \int_{\bar{\omega}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\omega}_{+} \right] d\theta \\ < 0 &\end{aligned} \tag{8}$$

When $h_x(x) > 0$, the interior sign of the brackets is negative by Lemma 3.1. Therefore, index insurance will increase input use for risk increasing inputs.

A contract built with θ principle will follow equations Equation 6 - Equation 8 with the only difference being in the integral bounds and the differential variables.

$$\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} \overbrace{j_\omega(\omega) J(\bar{\theta})(1 - J(\bar{\theta})) u''(\omega, \cdot)}^{-} \left[\int_{-\infty}^{\bar{\theta}} \underbrace{j_\theta(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\theta - \int_{\bar{\theta}}^{\infty} j_\theta(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\theta}_{-} \right] d\omega \tag{9}$$

$$> 0$$

Lemma 3.1 signs the 2nd term of Equation 9. The risk effects of inputs never changes the sign, so a contract built on θ will always increase optimal input use when θ and ω are uncorrelated.

□

Our specification of fishery index insurance shows that behavior change is possible in fishery index insurance. The direction of change from risk effects follows the same outcomes as demonstrated by Mahul (2001), Ramaswami (1993), and Bulte and Haagsma (2021) when biological and productivity risk are independent and triggered off productivity risk. Insurance provides risk protection lowering the necessity of risk decreasing inputs, therefore reducing their use and overall harvest. Insurance increases risk increasing inputs as it protects against additional risk allowing fishers to expand production without taking on greater risk.

Proposition 3.1 also provides new insight on how the selection of an index and its interaction with fisher risk leads to different behavioral responses in fishers. When both shocks are uncorrelated, the insurance only protects against indemnified risk. Fishers mitigate ω risk through risk decreasing inputs, thus they will decrease input use when insurance is structured on ω. However, fishers will always increase input use when insurance is structured on θ as the concave, risk increasing nature of $\theta f(X)$ will always expand production.

It is likely that the ω and θ are correlated to some extent. For example, strong winds can affect both fisher's ability to catch and biological upwelling. Therefore, we expand the proposition to include perfect correlation between θ and ω as a means to bookend the full range of possible correlations. In this unique case, basis risk is eliminated and insurance would provide protection against all sources of risk.

Proposition 3.2. *For feasible index insurance contracts specified at either trigger, $\bar{\omega} = 0$ or $\bar{\theta} = 0$, when ω and θ are perfectly correlated random variables, optimal fisher input is ambiguous when $h_x(x) < 0$ and increases when $h_x(x) > 0$.*

Proof. Perfect correlation implies $\theta < 0$ when $\omega < 0$ and $\theta > 0$ when $\omega > 0$ since both distributions have mean zero, $\mathbb{E}[\theta] \equiv \mathbb{E}[\omega] = 0$. The bounds of the integral can be with respect to either trigger. For simplicity, we will use $\bar{\omega}$ as the trigger, but the proof holds with $\bar{\theta}$.

$$\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\bar{\omega}} \int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) + (1-J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{\omega})) d\omega d\theta \\ + \int_{\bar{\omega}}^{\infty} \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega d\theta \tag{10}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 10.

$$\frac{U}{\partial x \partial \gamma} = u''(\cdot) J(\bar{\omega})(1-J(\bar{\omega})) \int_{-\infty}^{\bar{\omega}} \int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\omega) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega d\theta \\ - \int_{\bar{\omega}}^{\infty} \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega d\theta \tag{11}$$

By Lemma 3.2, when $h_x(X) < 0$ the interior is ambiguous so Equation 11 cannot not be signed, but is unambiguously positive when $h_x(X) > 0$.

□

Proposition 3.2 shows a tension arises when biological risks are correlated with productivity risks. Insurance replaces the variance reduction benefits of risk decreasing inputs incentivizing less use. However, less input use will also lead to less harvest. Fishers decide whether the relative loss in income for lower variance is worthwhile. When θ and ω are perfectly correlated with each other, insurance covers biological variance as well as productivity variance. Mitigating biological risk then encourages fishers to expand production as insurance compensates some of the additional increasing risk of $\theta f(X)$. Whether fishers reduce or increase harvest depends on the effect of many factors such as the relative proportion of risk decreasing or increasing capacity of the input, degree of risk aversion, and the relative magnitude of variance between shocks.

Index insurance has the potential to enhance conservation or impede it depending on the resulting change in harvest. Fish abundance has simple elasticities to harvest so that decreases in harvest will correspond to increases in fish stocks. Therefore, analyzing only the effects of insurance on fisher input use is sufficient to determine the overall direction of impact on fish stocks.

In uncorrelated settings, there are clear changes to input use that will impact long term sustainability of fisheries. Any contract built on a θ shock will lead to increased harvest pressures. The leading candidates for possible indices in fisheries index insurance are currently weather variables most often associated with biological risks (Watson *et al.* 2023). Designing contracts solely on these variables may lead to harvest increases that run contrary to conservation goals.

Fisheries that use risk decreasing inputs will see lower harvest pressures, potentially leading to conservation gains when protected with insurance contracts that mitigate production risk in ω. Identifying the risk effects of fishing inputs ex-ante may be a challenge. Additionally, it is far more likely that weather variables will have some degree of correlation. The ambiguity of change in cases where the weather variables are correlated prevents clear predictions. Regardless, knowing the potential implications of index insurance induced behavior change will be important for policymakers to address long term sustainability.

The ambiguity of behavioral change makes it challenging to unequivocally sign the direction index insurance will impact harvest decisions. We will parameterize an insurance model with production elasticity estimates from Norwegian fisheries to numerically simulate the potential changes in harvest. However, Asche *et al.* (2020) estimated multiple inputs. This accurately reflects the complexity of fishery production, but it also introduces new interactions between insurance and input use that is beyond the simple one input model of Proposition 3.1 and Proposition 3.2. In order to determine the overall impacts of insurance in an empirical setting, we need to understand how insurance interacts with multiple inputs.

In the next section, we extend the insurance model to account for multiple inputs, and show how input decisions now must account for mean input elasticities and the cross partials of risk effects on production. Theoretical results indicate that further ambiguity is introduced with multiple inputs that deviates from the clarity of a simple one input model.

4 Insurance with multiple inputs

We simplify the general model in Equation 3 by using two inputs, $X \in \{x_a, x_b\}$ to understand the impact of insurance on multiple fishery inputs. Adding more variables complicates the model without adding any additional insights. The complexities of input interactions sufficiently arise with two inputs to demonstrate our intended purpose.

We postulate reasonable assumptions on the second derivative of the production risk function to assist with comparative statics later on. The marginal impact of adding an input to production variance should have diminishing effects, because it is impossible to completely eliminate risk or experience infinite risks. Therefore, when $h_{x_a}(X) > 0 \rightarrow h_{x_a x_a}(X) < 0$, and when $h_{x_a}(X) < 0 \rightarrow h_{x_a x_a}(X) > 0$. The cross partial of risk effects on production $\frac{\partial h}{\partial x_a \partial x_b}$ must also be flexible and depend on how inputs interact with each other. For example, if adding an input does not contribute to the marginal risk effect of another input then $\frac{\partial h}{\partial x_a \partial x_b} = 0$. Inputs interactions could be complementary in that adding a risk decreasing input further enhances the risk reducing properties of the other inputs, $\frac{\partial h}{\partial x_a \partial x_b} > 0$. In other instances the inputs may interact counter actively in that adding more of a risk increasing input might reduce the effect of a risk decreasing input, $\frac{\partial h}{\partial x_a \partial x_b} < 0$. In principle, when inputs share the same direction of risk effects, their cross partial ought to be complementary, and when inputs have opposite risk effects they will be counter productive.

We use the same insurance design from the previous section. Allowing multiple inputs with either risk increasing or risk decreasing effects presents a more complete and nuanced understanding of potential interactions. Fishers now maximize expected utility by selecting two inputs.

$$
\begin{aligned}
U \equiv \max_{x_a, x_b} \mathbb{E}[U] = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta) u(\pi(X,\hat{B},\theta,\omega) + (1 - J(\bar{z}_i))\gamma) d\omega \\
& + \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta) u(\pi(X,\hat{B},\theta,\omega) - J(\bar{z}_i)\gamma) d\omega \Bigg] d\theta
\end{aligned} \tag{12}
$$

Taking the first order conditions yields:

$$
\begin{aligned}
\frac{\partial U}{\partial x_a} = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta) u_{x_a}(\pi(X,\hat{B},\theta,\omega) + (1 - J(\bar{z}_i))\gamma) \frac{\partial \pi}{\partial x_a}(X,\hat{B},\theta,\omega) dz_i \\
& + \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta) u_{x_a}(\pi(X,\hat{B},\theta,\omega) - J(\bar{z}_i)\gamma) \frac{\partial \pi}{\partial x_a}(X,\hat{B},\theta,\omega) dz_i \Bigg] dz_r \\
\frac{\partial U}{\partial x_b} = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta) u_{x_b}(\pi(X,\hat{B},\theta,\omega) + (1 - J(\bar{z}_i))\gamma) \frac{\partial \pi}{\partial x_b}(X,\hat{B},\theta,\omega) dz_i \\
& + \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta) u_{x_b}(\pi(X,\hat{B},\theta,\omega) - J(\bar{z}_i)\gamma) \frac{\partial \pi}{\partial x_b}(X,\hat{B},\theta,\omega) dz_i \Bigg] dz_r
\end{aligned} \tag{13}
$$

Given the first order condition is satisfied, we can use the implicit function theorem (IFT) to look at the impact of a change in the exogenous insurance contract locally at the input solutions. Applying IFT and Cramer's Rule yields a system of equations that determine the impact of insurance on each optimal input:

$$
\begin{aligned}
\frac{\partial x_a}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{\partial U}{\partial x_b \partial x_b} \frac{\partial U}{\partial x_a \partial \gamma} - \frac{\partial U}{\partial x_a \partial x_b} \frac{\partial U}{\partial x_b \partial \gamma} \right] \\
\frac{\partial x_b}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{-\partial U}{\partial x_b \partial x_a} \frac{\partial U}{\partial x_a \partial \gamma} + \frac{\partial U}{\partial x_a \partial x_a} \frac{\partial U}{\partial x_b \partial \gamma} \right]
\end{aligned} \tag{14}
$$

Because the determinate will always be positive by the definition of the second order condition, we can focus on the interior of the brackets. If positive, then insurance will lower use of that specific input and vice versa if negative. The partial derivatives are necessary to sign Equation 14. Their complete derivations are included in the appendix. The complex interaction between the partial effects of inputs and insurance presents a challenge to understanding the impacts of index insurance on fisheries. Therefore, we only focus on the uncorrelated case where θ and ω are independent. Ambiguity already exists with some correlation. Introducing additional ambiguity only obscures insight further.

Specific conditions must be met to determine the overall impact of index insurance on inputs, otherwise the effect could go either way despite the risk increasing or decreasing characteristic of an individual input.

Proposition 4.1. *In fisheries with two inputs, when θ and ω are uncorrelated, index insurance will change the optimal use of a specific input in accordance to an input's own risk effect when the following sufficient condition is true:*

$\frac{\partial U}{\partial x_a \partial x_b} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial U}{\partial x_a \partial x_b} < 0$ *when inputs have opposite risk effects.*

Otherwise, Index Insurance will have ambiguous effects on optimal input choice.

The proof is included in Section A.4 and follows similar steps as the proof of Proposition 3.1 while accounting for the partial effects of each input.

Proposition 4.1 shows that index insurance can have clear impacts on input use even in complex settings with multiple inputs provided the sufficient condition holds. However, it is not clear ex-ante what the sign of the cross partial inputs of the first order condition should be. Essentially, fishers change their inputs depending on whether a given input makes the other input more productive than the risk it adds. Whether inputs are complementary or counteractive in their risk effects influence the sign of the cross partial. When inputs share risk effects, they ought to increase the risk effects of each other. Therefore the cross partial is more likely to be negative when inputs share risk effects and positive when they are complementary following the sufficient conditions proposed in Proposition 4.1.

Even with two inputs, ambiguity on the optimal use exists. Extending to more inputs introduces more interactions among the inputs, and the relatively weighting between marginal productivity and the risk effect cross partials is even harder to sign. Ramaswami (1993) used this complexity as a justification to only examine the total variance of production with a vector of inputs. Proposition 4.1 helps elucidate his observations, while providing some understanding of how different inputs could change when fishers use a variety of inputs. Specific inputs could have different external environmental and community impacts. Being better able to predict how index insurance changes those inputs, and their ensuing impacts on a fishery, will help minimize any negative impacts that could arise.

Despite the seemingly rigid conditions, Proposition 4.1 provides useful insight into the behavioral effects insurance will have when fishers use multiple inputs. It states that when the conditions hold, the direction all inputs should change is based solely on the characteristics of their own risk effects. Other inputs may influence the magnitude of change, but the direction is unequivocal. It remains unclear what the overall impacts on harvest will be in a multiple input setting. Differences in mean production elasticity lead to different magnitudes of change in input use. The overall change in harvest, and thus conservation, depends on the aggregate change in harvest. For example, a decline in use for a risk decreasing input compared to an equivalent increase in use of a risk increasing input may not lead to lower harvest if the risk increasing input is relatively more productive.

The next section uses simulations to show the total impact on harvest can vary substantially, and that the conditions to ensure unambiguous input change can be met. Though when applied with real world estimates of risk effects, the conditions may not hold and the effects of index insurance does not follow simple rules.

5 Numerical Simulations

We use numerical simulation to show the ambiguity present in Proposition 3.2 and to determine the magnitude of change in input use for Norwegian fisheries using the parameters found in Asche *et al.* (2020). Monte Carlo simulations find expected utility across 1000 random draws of productivity and biological shocks. A comprehensive set of parameters test the sensitivity of fisher input choices with index insurance. All simulations are conducted in R with accompanying code available at [WILL ADD ONCE REPO IS CLEANED].

5.1 Simulations with one input

We use the structural form where $f(x) = x^\alpha$ and $h(x) = x^\beta$ to most easily integrate risk increasing or decreasing effects in $h(x)$ (Equation 15). Mean production $f(x)$ is concave so that $\alpha > 0$. Risk effects on the input can either be risk increasing or decreasing with $\beta \lesseqgtr 0$. We apply convex costs, $c(x) = cx^2$, for smoother convergence in the maximization procedure. Biological and productivity shocks are normally distributed with $\theta \sim N(0, \sigma_\theta)$ and $\omega \sim N(0, \sigma_\omega)$. The shocks are linked through a copula with correlations ranging from $[0, 1]$.

$$\pi = x^\alpha(\hat{\beta} + \theta) + \omega x^\beta - cx^2 \tag{15}$$

Fishers will choose inputs x to maximize expected utility with an exogenous insurance contract. Constant Absolute Risk Aversion (CARA) utility is used to better account for negative shocks and profit loss. We examine insurance built on ω first to test the more ambiguous cases (Equation 16).

$$\begin{aligned} U &\equiv \max_x \mathbb{E}[u] = \mathbb{E}[(1 - \exp(-a(\pi(x, \hat{\beta}, \theta, \omega) + \mathbb{I}(\gamma))] \\ \mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\gamma & \text{if } \omega < \bar{\omega} \end{cases} \end{aligned} \tag{16}$$

We convert γ to be a percentage of mean optimal profit without insurance for interpretability. For example, $\gamma = 1$ would represent a payout equivalent to expected profit before insurance, and $\gamma = 0$ represents no insurance. The insurance contract is triggered by $\omega < \bar{\omega}$.

We create a wide parameter space to assess the sensitivity of optimal input choices to different model parameters. We vary the relative productivity of the input $\alpha \in \{0.25, 0.5, 0.75\}$, the risk effect of the input $\beta \in \{-0.7, -0.5, -0.3, -0.1, 0.1, 0.3, 0.5, 0.7\}$, the risk aversion parameter $a \in \{1, 2, 3\}$, the biological shock variance $\sigma_\theta \in \{0.1, 0.2, 0.3, 0.4\}$, the productivity shock variance $\sigma_\omega \in \{0.1, 0.2, 0.3, 0.4\}$, and the correlation between the shocks ranging from 0 to 1 with 0.2 steps.

First we iterate γ from 0 to 1.5 to show the change in optimal input use for a single input. Selected parameters for Figure 1 are for demonstration purposes. The full parameter space is explored in the accompanying code.

Optimal input use changes monotonically with index insurance depending on the risk characteristics of the input (Figure 1). Risk increasing inputs always increase with insurance. Risk decreasing inputs are ambiguous following Proposition 3.1 and Proposition 3.2. Independent shocks lead risk decreasing inputs to monotonically decrease with ω contracts. Risk decreasing inputs will monotonically raise or lower with an insurance contract built on ω when correlated with θ.

The concavity of utility, as demonstrated by the blue parabolas in all panels of Figure 1, implies there exists an optimal amount of insurance for fishers to buy. The monotoncity of input use in all cases suggests that the insurance level that maximizes utility will persevere the sign of input changes. Therefore, an endogenous choice of insurance will not affect the direction of input change, but it will affect the magnitude.

For example, risk increasing inputs have higher levels of insurance payouts that maximize utility. Allowing fishers to choose insurance coverage ensures that the choice of insurance and input use changes are welfare improving and will not bias input choices with over or under investment of insurance. Simulations moving forward will allow fishers to choose both inputs and insurance coverage.

Adding an endogenous to Equation 16 amends the choice set in Equation 17. Furthermore, we run two groups of simulations. One with the insurance contracted indemnified on ω as shown in Equation 16, and another with the index built on θ to test all conditions of Proposition 3.1 and Proposition 3.2.

$$
\begin{aligned}
&U \equiv \max_{x,\gamma} \mathbb{E}[u] = \mathbb{E}[(1 - \exp(-a(\pi(x, \hat{\beta}, \theta, \omega) + \mathbb{I}(\gamma))] \\
&\mathbb{I}(\gamma) = \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\gamma & \text{if } \omega < \bar{\omega} \end{cases}
\end{aligned}
\tag{17}
$$

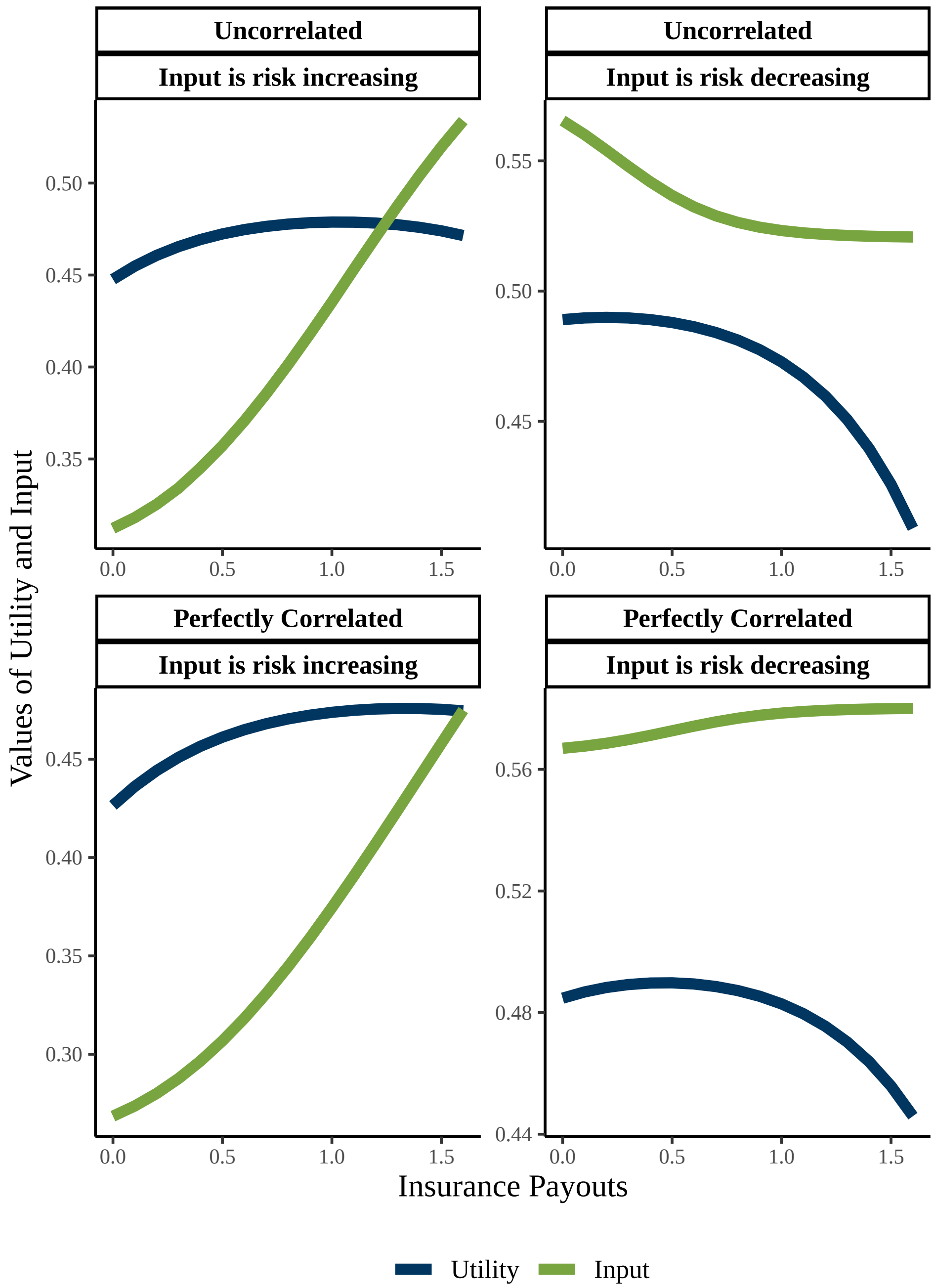

Figure 1: Improvements in utility (green lines) and changes in optimal input use (blue lines) with index insurance. Shocks are uncorrelated with high mean productivity ($\alpha = 0.75$), high risk aversion $a = 3$, and relatively more variable weather shocks than biological ($\sigma_w = 0.4$ vs $\sigma_t = 0.1$)

Correlation between biological and productivity risk impact optimal choice of input in line with Proposition 3.1 and Proposition 3.2 when contracts use ω as the index. Uncorrelated shocks have consistent signs of input use in accordance to the underlying inputs risk effect function (Figure 2). Insurance lowers risk decreasing inputs, but at smaller margins when productivity is high. Insurance raises risk increasing inputs at similar margins for all levels of productivity. This result verifies Proposition 3.1 for ω index contracts.

Perfectly correlated shocks, shown by the far right cluster of bars in each panel of Figure 2, verify the results of Proposition 3.2. Insurance always raises risk increasing inputs, but has ambiguous effects on risk decreasing inputs. The tradeoff between the risk reducing capacity of the inputs and its marginal productivity drives this result. Because the variables are perfectly correlated, insurance protects against both biological and production risk. Insurance decreases the need to reduce productivity risk through $h(x)$, but increases the desire to take on more biological risk to achieve greater harvests. Which of these effects dominates depends on how productive is the input. Inputs with low productivity do not provide as much benefit when taking on further biological risk, so fishers will decrease their use if the input is risk decreasing. Very productive inputs provide excellent marginal returns and it becomes worthwhile to pursue additional harvest as insurance protects the additional risk.

The more correlated the variables, the stronger the effect. Perfectly correlated indices imply zero basis risk and would be considered "perfect" contracts. The behavioral implications of our model suggest that this form of basis risk could lead to more conservation degradation than imperfect uncorrelated contracts. However, basis risk is a significant impediment to insurance uptake (Binswanger-Mkhize 2012; Clarke 2016). The average improvement in utility for contracts with high basis risk was 1.5%, and 7.8% for "perfect" contracts implying that fisher demand would be much higher for the perfect contract. If policymakers want to promote well designed contracts, there must be other considerations to curtail harvest expansion otherwise long run sustainability will be impeded.

Figure 3 verifies the remaining properties of Proposition 3.1 and Proposition 3.2. Contracts built on θ as the index show more bias towards overfishing because of the inherent risk increasing characteristics of $f(x)$. Uncorrelated shocks imply that insurance will only protect shocks on θ. Production can expand as insurance protects the additional risk of $\theta f(x)$ regardless of the risk decreasing inputs. The results become ambiguous when the shocks are correlated for the same reasons as when contracts are built on ω. The overall protection offered by insurance will allow whichever marginal effect between $hx_(x)$ and $f_x(x)$ to dominate the direction of optimal input use.

Magnitude of input changes are sensitive to other parameters. More risk averse fishers respond more aggressively to insurance and make relatively more changes toward their input decisions (Panel A in Figure 4). Risk aversion implies more sensitivity towards risk. The protection from insurance has greater marginal value for more risk averse fishers. Greater marginal value of insurance means they can invest less into risk reducing inputs than before, and have more protection from greater shocks with risk increasing inputs.

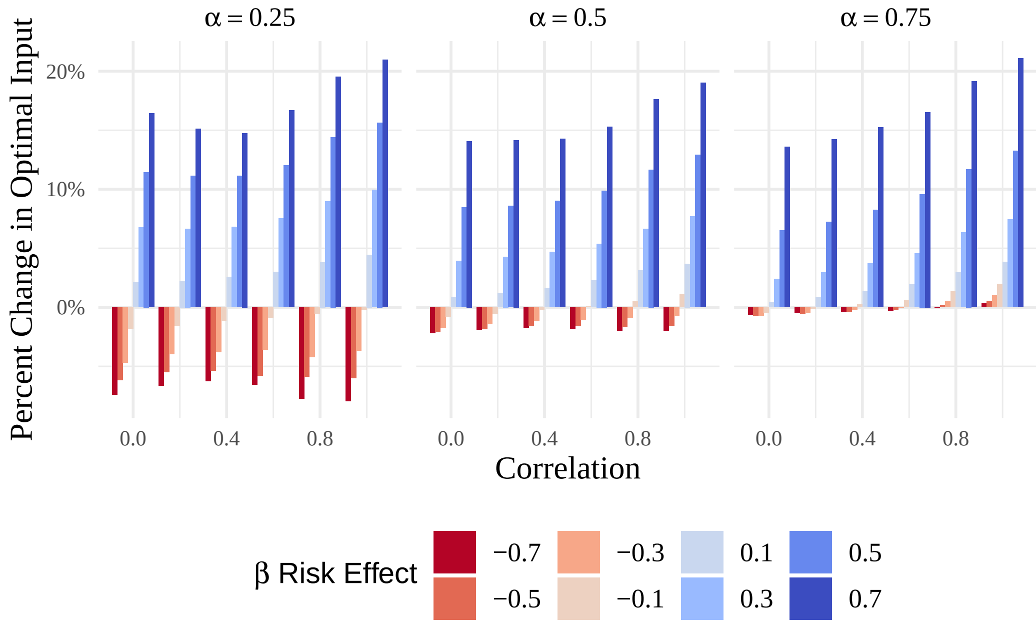

Figure 2: Percentage change in optimal input with an index insurance contract using ω as the index. Risk increasing inputs (blue bars) always increase input use, while risk decreasing inputs (red bars) have ambiguous effects depending on the basis risk (correlation on the x-axis) and relative productivity of the input (α in the panels).

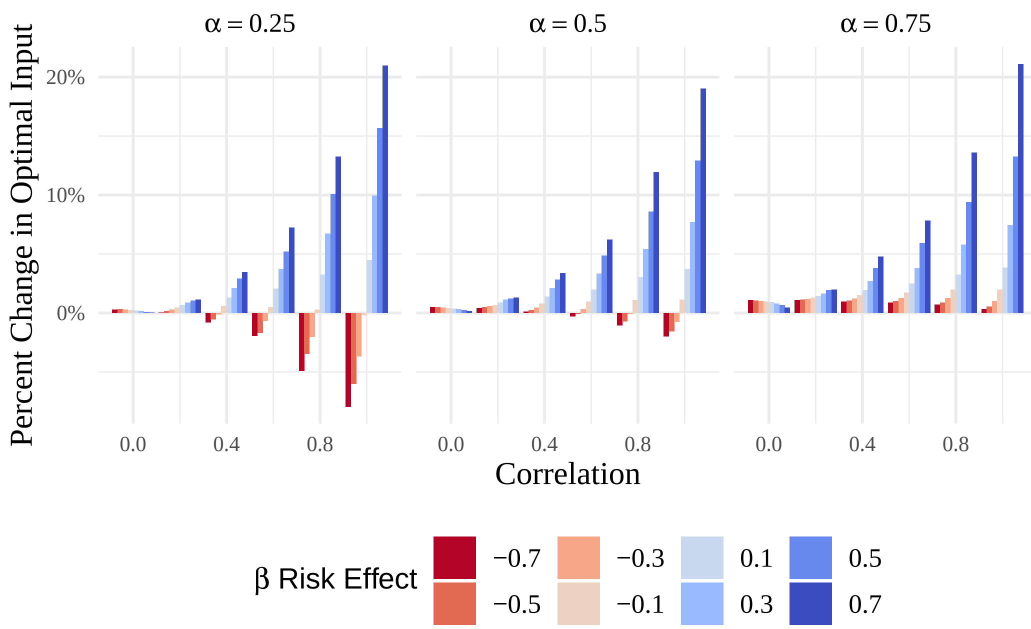

Figure 3: Percentage change in optimal input with an index insurance contract indenmified on θ. Higher corrleations (x-axis) lead to amiguous results where ω risk decreasing inputs (red bars) could lead to decreases in input use. Panels indicate the biological production elasticity. Risk increasing inputs (blue bars) always lead to greater input use.

Fisher input choice are much more responsive to insurance protection from larger productivity risks (Panel B Figure 4). Similar to risk aversion, the greater the shocks the greater the marginal value of insurance is to mitigate those shocks. In more volatile environments, insurance provides significantly more income smoothing leading to similar incentives as the higher risk aversion example.

Trigger levels do not appear to have differing impacts on input use. Setting the trigger levels to more catastrophic coverage did not encourage fishers to change their input use relative to the other parameters. While necessary for applying Lemma 3.1 and Lemma 3.2 in the proofs, the results of Proposition 3.1 and Proposition 3.2 would appear to hold if $\bar{\omega} \neq 0$.

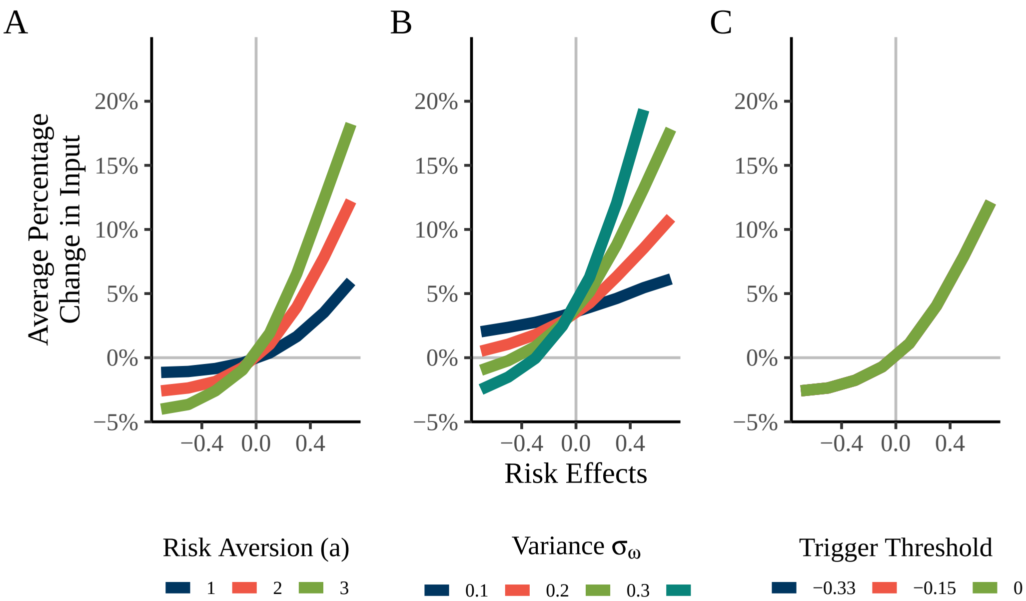

Figure 4: Risk Aversion (A), weather variance ω (B), and trigger (C) all influence the magnitude of change in harvest. Mean production elasticity is set to 0.5. Average percent change in input (y-axis) is summarized across all other parameter combinations for each risk effect value of β.

In the next section we use parameters from Asche *et al.* (2020) to calculate the overall change in harvest with multiple inputs interacting with index insurance.

5.2 Application to Norwegian Fisheries

Asche et al., (2020) aggregated by vessel type and not species, so there is no reasonable estimate for biomass. They accounted for biomass using fixed effects in their regression, but without additional information we cannot parameterize the mean and variance of biomass. Therefore, our simulations normalize mean biomass to 1 and we assume the biomass shocks, θ, have three degrees of correlation with ω, $\{0, 0.5, 1\}$. Norwegian fisheries are well managed so the biological variance could be mitigated through quota systems or accurate stock assessments. The simulation model uses three inputs (capital k, labor l, and fuel f) instead of one (Equation 18).

$$\pi(k, l, f) = k^{\alpha_k} l^{\alpha_l} f^{\alpha_f} (\hat{\beta} + \theta) + \omega k^{\beta_k} l^{\beta_l} k^{\beta_f} - c_k k^2 - c_l l^2 - c_f f^2 \tag{18}$$

Fishers in the simulation choose inputs and insurance coverage to maximize expected utility. We use either index as shown by z.

$$\begin{aligned} U &\equiv \max_{\gamma,k,l,f} \mathbb{E}[u] = \mathbb{E}[u(k^{\alpha_k} l^{\alpha_l} f^{\alpha_f} (\hat{\beta} + \theta) + \omega k^{\beta_k} l^{\beta_l} k^{\beta_f} - c_k k^2 - c_l l^2 - c_f f^2 + \mathbb{I}(\gamma)] \\ \mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } z \geq \bar{z} \\ (1-\rho)z & \text{if } z < \bar{z} \end{cases} \end{aligned} \tag{19}$$

Table 1 shows the production and risk elasticities of the four vessel types used in the simulation. While not all elasticities were found to be statistically different from zero, we used their raw values because dropping only those variables that are significant in both matching parameters would have kept only a few valid combinations. All non-significant elasticities led to small changes as expected, but their interactions with other inputs could partially drive some of the observed outcomes.

Table 1: Production and Risk elasticities of Norwegian Fisheries from Asche et al., (2020)

	α_k	α_l	α_f	β_k	β_l	β_f
Coastal Seiners	0.294	0.421	0.457	0.184	-0.432	0.119
Coastal Groundfish	0.463	0.421	0.355	0.965	-0.080	0.113
Purse Seiners	0.941	-0.108	0.605	-0.454	-0.231	0.160
Groundfish Trawlers	0.210	0.106	0.531	-2.788	-0.110	-0.024

We use the same parameter space as the previous simulations to test the sensitivity of fisher input choices with index insurance. We plot the distribution of input change after insurance for all combinations of parameters for each fishery in Figure 5 based on a contract with ω as the index. We report the highest density as an indicator of the general direction of input change, but the distribution shows that mixes of risk increasing and decreasing inputs can lead to ambiguous results.

We also examine Proposition 4.1 by isolating the input use change in each fishery through density plots in Figure 6.

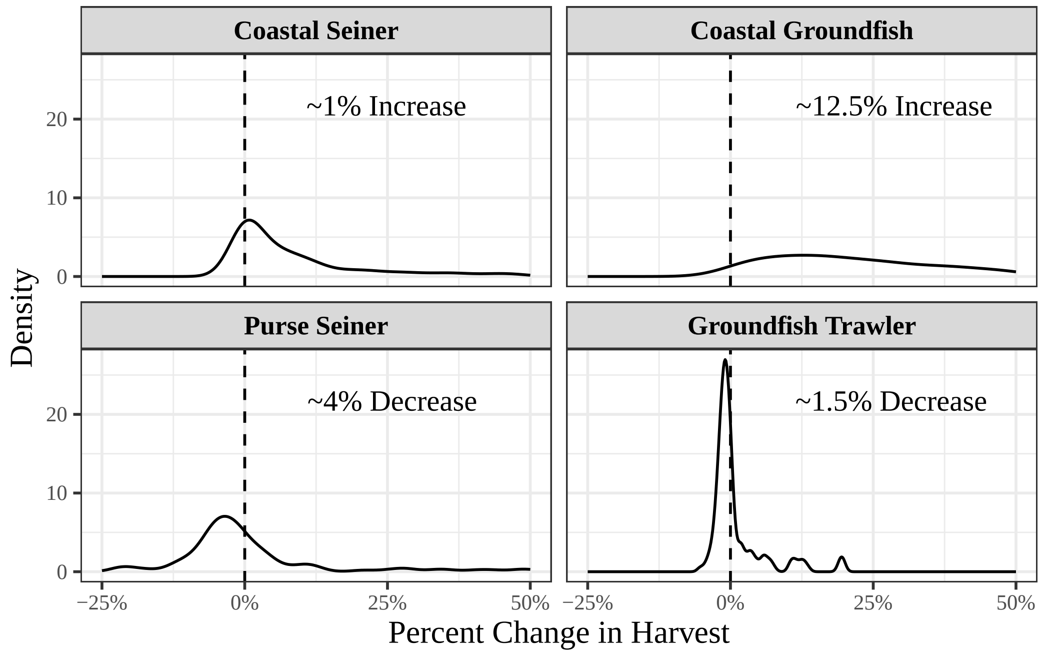

Figure 5: Density plots of the percent change in harvest for each vessel type in Norwegian fisheries. The dashed line represents no change in harvest. The text labels represent the median percent change in harvest for each vessel type.

Overall, insurance leads to relatively small changes in harvest for all fisheries, but increases are stronger than decreases. Coastal groundfish see the largest and most consistent increase in harvest. Median harvest increased by 12.5% with a max increase of 50%. Coastal groundfish have the most risk increasing inputs out of the estimated fisheries. Labor is the only risk decreasing input in the coastal groundfish fishery at a minuscule -0.08. Coastal groundfish show a case where the conditions of Proposition 4.1 do not hold. Labor always increases despite being a risk decreasing input (Figure 6). Increased captial and fuel use contribute the most to the increased harvest.

Coastal Seiners had a relatively balanced spectrum of risk effects. The input mix in this case led to both increases and decreases in input use, which on net led to near zero changes in harvest. There is a slight skew towards increased harvest, but drastically less than the coastal groundfish fishery. Proposition 4.1 does hold in this fishery as each input follows their respective increase or decrease contingent on their risk effects (Figure 6).

Deep water fleets generally saw reductions in harvest. Purse Seiners tended to decrease harvest by 4%. Labor is never used in the simulations because of the negative mean productivity elasticity so it is removed from Figure 6. Capital is the most productive input with the strongest risk effect. It appears to control the direction of overall harvest. The conditions of Proposition 4.1 do not hold as there are some parameter combinations that lead risk decreasing capital to increase and risk increasing fuel to lower with insurance.

Groundfish trawlers consistently see small decreases of 1.5% in harvest (Figure 5). All inputs are risk decreasing with capital having the strongest risk effect out of all inputs across all fisheries. However, it has a relatively low marginal productivity. Insurance decreases trawler capital use by about 8%, but the low productivity leads to only a 1.5% decrease in overall harvest. Labor and fuel see small declines in use that are always negative. When correlations are allowed, there are some instances that see increases in harvest matching the observations of Proposition 3.2. The conditions of Proposition 4.1 are met in this fishery as expected because each input shares the same risk effect (Figure 6).

Applying an insurance contract indemnified on θ instead of ω shows similar results, but shifts the direction towards more overfishing (Figure 7). The most prominent shifts occur in the groundfish trawlers and coastal seiner fleets. In Figure 5, the percent change in harvest for coastal seiners is indistinguishable from zero. With a θ index contract, there is now a pronounced shift towards overharvesting (Figure 7).

Groundfish trawlers have opposite results with a contract indenmified on θ. Despite the risk decreasing dominance of capital, fishers will choose to increase production as insurance drastically protects against the added harvest risk. This result most clearly shows the impact of different insurance contracts and the potential for maladatpive behavior change. Without considering all the margins for change, insurance protecting against biological risk will still encourage overfishing without additional constraints.

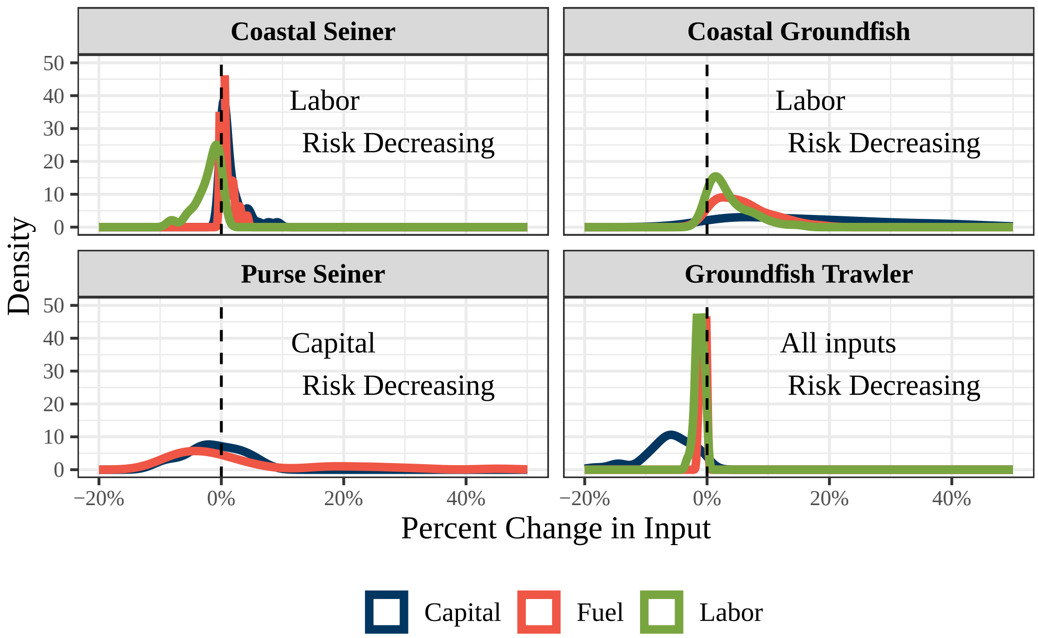

Figure 6: Density plots of the percent change in input use for each vessel type in Norwegian fisheries. The dashed black line represents no change in input use. Risk decreasing inputs are labeled. Labor (green lines) is dropped for Purse Seiners because labor was never used in simulations due to negative productivity elasticity.

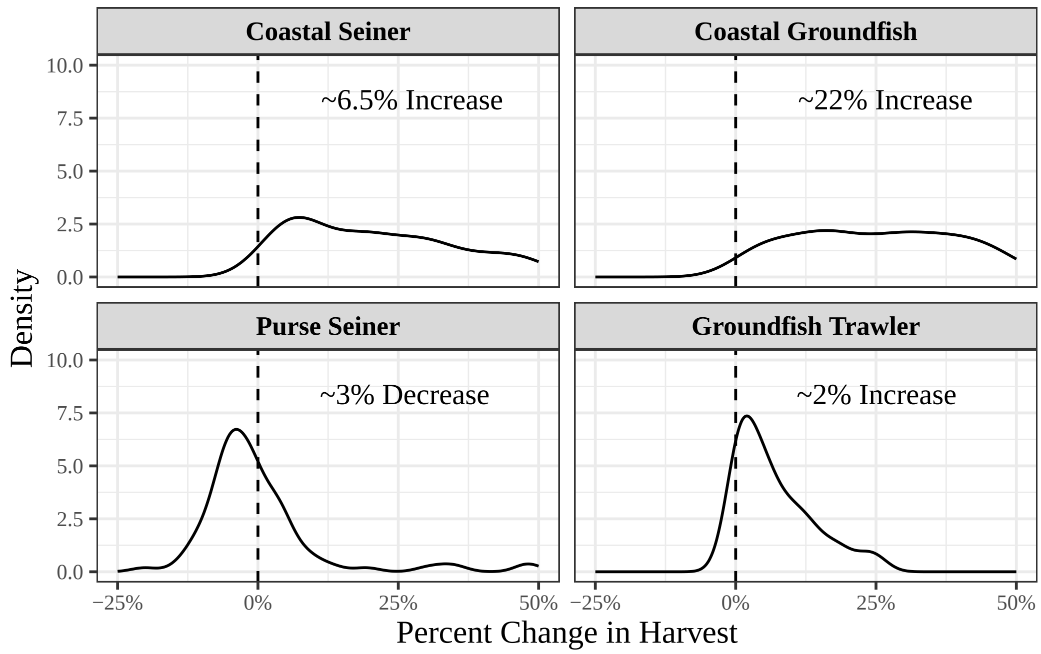

Figure 7: Density plots of the percent change in harvest for each vessel type in Norwegian fisheries with insurance contract indemnified on biological risk θ. The dashed line represents no change in harvest. The text labels represent the median percent change in harvest for each vessel type.

6 Discussion

This paper makes three distinct contributions. First, index insurance will have behavioral impacts on fishers' input decisions, which in turn will lead to changes in fishery sustainability. Second, the design of index insurance contracts affects policyholder behavior contingent on the mitigation strategies available to protect the underwritten risk. Third, fishers face distinct sources of risk through the biology of fish stocks and inherent harvesting variability that can be modeled with a new stochastic production function.

The fundamental driver of fishers' behavior changes is whether the marginal change in productivity is balanced by the marginal change in risk. Fishers are more willing to increase production if insurance negates the additional risk of expanded production. Since insurance lowers risk, fishers need less self insurance through risk reducing inputs and can reduce their overall input use. However, using less inputs implies less catch and revenue creating a unique tension that exists throughout the analysis. Across all simulations, decreased input use was smaller than increased input use holding all other parameters constant. Behavior change in fisheries will lean towards expanding production creating a dilemma for conservation efforts.

Index insurance would improve welfare in Norwegian fisheries, but also lead to changes in harvest that depends on the production risk effects of fishing fleets. Coastal groundfish trawlers increased fishing pressures by 12.5% when offered insurance. Capital and fuel are risk increasing inputs, and encourage the increased harvest. If an insurance policy was applied to provide the income smoothing benefit of insurance, the policymaker must take measures to mitigate the preserve incentive to expand fishing production. Otherwise, the long term health of the stock could be degraded and fishers would be worse off in the long run (Müller *et al.* 2017; John *et al.* 2019; Bulte and Haagsma 2021).

Norwegian pelagic groundfish trawlers would have the opposite considerations. When offered insurance they reduced their harvest by 1.5%. Though small, it will lead to improved fishery sustainability. The long term benefit of insurance would increase with improved stock health. The decline in harvest was driven by a reduction in overcapitalization, because capital was a significantly risk decreasing input. Policymakers should attempt to identify fisheries with risk decreasing input for insurance contracts to improve sustainability if index insurance is to operate in isolation of other policies.

Ex-ante idenfication of input risk effects is challenging. Production risk effects remain an elusive concept in fisheries, and need to reconciled in order to articulate more accurate behavior changes of fishery index insurance. Crop covers and pesticide provide clear examples of risk decreasing inputs in agriculture, but what do risk decreasing inputs look like in fisheries? Asche *et al.* (2020) provide empirical evidence of the existence of risk decreasing inputs, but do not elaborate on why or how labor and capital directly decrease risk. Labor is perhaps the more intuitive risk decreasing input. Technical expertise of crew and captains can hedge against luck when fishing (Alvarez *et al.* 2006). Better trained crew can deploy gear in a safe and timely manner, increasing the likelihood of effective sets.

Fuel as a risk increasing input in fisheries makes intuitive sense as well. Fuel is used to power vessels and is a direct cost of fishing. Fishers explore productive fishing grounds for the best location. Every hour at sea increases the harvest reward, but also the chances of failure.

Capital is a more complex input, because it is shown to be both risk increasing and decreasing. Capital investments in fisheries typically refer to vessel tonnage, engine power, and gear technology. The spatiotemporal dimension of fishing decisions may explain how capital can potentially possess both risk effects. Fishers have to make decisions on where, when, and how long to fish that differ from the set grids of agriculture (Reimer *et al.* 2017). Capital offers protection from risk by allowing fishers to explore more fishing grounds, use more secure gear, and fish in more adverse weather conditions. When common pool resources incentivize the race to fish, having larger vessels may be a risk reducing input as the sooner a fisher harvests from the stock, they assure their income at the expense of other fishers. Adding risk aversion to standard models of common pool fisheries suggests fishers should lower their capital use compared to risk neutral allocations (Mesterton-Gibbons 1993; Tilman *et al.* 2018). Yet, overcapitalization and overfishing are more often observed in the real world. Either fishers are never risk averse or the risk effects of capital are not as simple as the standard model suggests. When capital is allowed to be risk decreasing, optimal input choices are much higher than risk neutral equilibrium suggesting fishers are making rational, risk averse decisions even while overfishing.

Fishers exposure to multiple sources of risk further necessitates insurance, but also makes it more challenging to design. Proposition 3.2 shows the interaction between the biological and production risk obfuscate the moral hazard of insurance. The assumed volatility of more fish in the ocean leads the harvest function to implicitly be risk increasing in our specification of stochastic production. With this assumption, designing a contract around a primarily biological shock will bias the results towards more overfishing. In the Norwegian fisheries, contracts built on biological risk increased median fish harvest in all fisheries. Median fish harvest rose precipitously by 22% in the risk increasing coastal groundfish. One simple step for policymakers to avoid perverse moral hazards would be to avoid index insurance contracts triggered on weather variables that impact biomass.

However, most bioeconomic models simplify the complex effects of stock dynamics into multiplicative forms as modeled in this paper. Instead, different forms of risk could be embedded into the biological component of fishery models. Stock variance could be greater in overfished stocks instead of healthier ones, reflecting more vulnerability in weaker states (Sims *et al.* 2018). Adapting alternative, more biologically focused specifications of biological risk could change the behavioral effects of insurance. If insurance protects from more risk, fishers may be more willing to expose themselves to greater risk at more vulnerable stock levels. Alternatively, insurance could help mitigate risk and incentivize fishers to move toward healthier stocks with less variance by alleviating pressures to fish. Further analysis is required to understand the full implications of biological risk effects in fisheries.

Selecting suitable fisheries is equally as important as selecting the right contract. Moral hazards exist and will have noticeable effects on fishing production. Further considerations must be taken into account of the impacts of index insurance.

The transfer between inputs and insurance reflects the substitution between self-insurance and formal insurance (Quaas and Baumgärtner 2008). If index insurance is designed to reduce fishing capacity, efforts must be made to ensure that it does not take away from the self resiliency of fishers. Labor appears to be consistently risk reducing and acts as a form of self insurance. If index insurance incentivizes captains to hire less crew, the stock of fish may be preserved, but less employment may reverberate throughout the community. Fishing is often a primary employment opportunity in coastal communities. The resiliency of the community would be compromised rather than enhanced with fewer jobs. The same idea applies to capital. If fishers are over investing in capital to hedge against some form of risk, policymakers need to be sure the insurance is replacing maladaptive self insurance behavior.

The primary form of self insurance in fisheries is management. To this point our analysis explicitly modeled scenarios without the existence of management. Most fisheries are managed in some form. The interaction between management and insurance may be complementary or substitutes. For example, well managed fisheries that have responsive harvest control rules may not need insurance. The management system is already providing the necessary risk protection. Insurance demand and uptake may be low in these fisheries. Insurance could instead complement management to provide the financial relief that management cannot offer. Managers often focus on the biological health of the fishery that can run at odds with fishers' desires to enhance their income. Insurance can act as the financial relief and allow managers to pursue more active strategies to protect fish stocks without political resistance from lowered quotas. Additionally, management can provide the constraints on insurance moral hazard so the income smoothing benefits are passed to fishers, but not the long term degradation. The interaction between insurance and management requires further investigation especially with the the numerous management strategies that exist in fisheries.

Design and access of insurance must also consider equity. The current US federal disaster relief program is inequitable with bias towards large industrial vessels (Jardine *et al.* 2020). Creating another program with equal inequity would be foolhardy. Current US farm subsidies, including insurance premiums, are heavily skewed towards large agribusinesses (White and Hoppe 2012). Dimensions of access, procedural, representation, and distribution must all be built into the design of new fishery index insurance programs (Fisher *et al.* 2019). For example, small scale fishers may have income constraints that prevent them from buying the initial contract. Micro-finance options connected to insurance have been used in agriculture to alleviate this burden with some success (Dougherty *et al.* 2021). Additionally, who receives the payouts needs thorough consideration. Payouts solely to vessel owners may ignore support to valuable, yet vulnerable fishery participants. Deckhands and crew are laid off during closures. If index insurance payouts are going through the entire fishery, the most vulnerable in the event of closures must be protected as well. Contract stipulations could mandate that only cost expenses are covered by payouts thereby including lost wages to the crew. Agriculture contracts often are designed to directly cover expenses (He *et al.* (2020)). Labor expenses could be included in the contract to ensure that the crew is protected as well.

Our model only directly models behavior change through moral hazards. Index insurance could be designed to incentivize other forms of sustainable behavior change. We define three pathways insurance can change behavior: Moral hazards, Quid Pro Quo, and Collective Action. Moral hazards were proven in this paper to have ambiguous impacts controlled by the risk characteristics of fishery inputs. The incentives of moral hazards will always exist, therefore other measures could be taken to either limit the downside behavioral effects of insurance or stimulate other forms of sustainable behavior.

Quid Pro Quo expands contract design to explicitly build in conservation measures. Fishers would be required to adopt sustainable practices in order to qualify for insurance. Quid Pro Quo is already used in agricultural insurance in the form of Good Farm Practices. Farmers must submit management plans to US Risk Management Agency that clearly outline their conservation practices in order to qualify for insurance. Working closely with management agencies, insurance companies could design contracts that require fishers to follow fishery specific management practices. For example, fishers may be incentivized to use more sustainable gear types, have an observer onboard, or reduce bycatch. Management input is needed to tailor fishery best practices to insurance contracts. Further research would need to uncover the full impact of Quid Pro Quo, but an initial hypothesis would be the fishers will be willing to adopt sustainable practices so long as the marginal gain in utility from the insurance is greater or equal to the necessary sustainable changes. Otherwise fishers will not want to buy the contracts and the insurance has no binding stipulations to change the fishery.

Collective action ties insurance premiums to biological outcomes to leverage the political economy of the fishery. Insures could reduce premiums in fisheries that have robust management practices such as adaptive harvest control rules, stock assessments, or marine protected areas in the vicinity. Fishers could either pressure regulators to adopt these actions or form industry groups to undertake the required actions. Insurers would agree to this if triggers are connected to biological health so that negative shocks are less frequent and thus payouts occur less. Fishers gain from the reduced insurance premium and the increased sustainability of harvest with rigorous management in place.

Ultimately, if index insurance is to be used in fisheries, it must be designed with clear objectives and intentions. Index insurance can meet objectives of income stability and risk reduction, but there has been an implicit assumption by practitioners that index insurance will always lead to improved sustainability. Without considering the behavior change of fishers when adopting insurance, the outcomes may not be as expected. New insights derived from this paper will help guide the efficient and sustainable implementation of fisheries index insurance.

A Appendix

A.1 Proof of Lemma 3.1

Lemma 3.1 *Individual fisher expected marginal profit of a specific input, x_m, is greater in the good state than expected marginal profit in the bad state when $h_{x_m}(X) > 0$. Expected marginal profit is higher in the bad state when $h_{x_m}(X) < 0$. If $h_{x_m}(X) = 0$, the marginal profits are equivalent in both states.*

By the first order conditions, there exist optimal values of any individual input x_m that must be chosen before the realization of the states of the world. Therefore $h(X^*)$, $f(X^*)$, and $c(X^*)$ are equal across states.

First we prove the case when $z \equiv \omega$. The steps and logic will follow nearly identically for θ.

Marginal utility in both states of the world is controlled by risk effects and the sign of the random variables. Given θ is independent of ω, the expected value of $\mathbb{E}[\theta|\omega \lesseqgtr \bar{\omega}] = 0$. The difference in expected marginal profit across insurance states is defined as:

$$\begin{aligned}\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x_m^*} =& \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] + \cancel{f_{x_m^*}(X^*)\widehat{B}} + \cancel{\mathbb{E}[\theta f_x(X^*)|\omega < \bar{\omega}]} - \cancel{c_{x_m^*}(X^*)} \\ &- \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}] + \cancel{f_{x_m^*}(X^*)\widehat{B}} + \cancel{\mathbb{E}[\theta f_x(X^*)|\omega > \bar{\omega}]} - \cancel{c_{x_m^*}(X^*)} \\ =& \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}]\end{aligned} \tag{20}$$

If an input is risk decreasing then $h_{x_m}(X) < 0$. Then Equation 20 is positive and marginal profit in the bad state is greater than the marginal profit in the good state. Adding more of a risk reducing input reduces the negative impact in the bad state relative to the good state.

$$\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}]}^{+}$$

Repeating the same steps for risk increasing inputs $h_{x_m}(X) > 0$ shows that marginal profit in the bad state is less than marginal profit in the good state.

$$\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}]}^{-}$$

When the insurance contract is triggered on biological risk θ, uncorrelated shocks will always lead to higher marginal profit in the good state. Uncorrelated shocks lead $\mathbb{E}[\omega|\theta \lesseqgtr \bar{\theta}] = 0$.

$$\frac{\partial \mathbb{E}[\pi|\theta < \bar{\theta}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\theta > \bar{\theta}]}{\partial x_m^*} = \cancel{\mathbb{E}[\omega h_{x_m^*}(X^*)|\theta < \bar{\theta}]} + \cancel{f_{x_m^*}(X^*)\widehat{B}} + \mathbb{E}[\theta f_x(X^*)|\theta < \bar{\theta}] - \cancel{c_{x_m^*}(X^*)}$$
$$- \cancel{\mathbb{E}[\omega h_{x_m^*}(X^*)|\theta > \bar{\theta}]} - \cancel{f_{x_m^*}(X^*)\widehat{B}} - \mathbb{E}[\theta f_x(X^*)|\theta > \bar{\theta}] + \cancel{c_{x_m^*}(X^*)}$$
$$= \mathbb{E}[\theta f_x(X^*)|\theta < \bar{\theta}] - \mathbb{E}[\theta f_x(X^*)|\theta > \bar{\theta}] \tag{21}$$

The concavity of $f(X)$ leads to $f_x(X) > 0$ always. Equation 21 can then be signed to always be negative so that marginal profit in the good state is always higher when insurance contracts are triggered on θ.

$$\frac{\partial \mathbb{E}[\pi|\theta < \bar{\theta}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\theta > \bar{\theta}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\theta f_{x_m^*}(X^*)|\theta < \bar{\theta}] - \mathbb{E}[\theta f_{x_m^*}(X^*)|\theta > \bar{\theta}]}^{-}$$

A.2 Proof of Lemma 3.2

Perfect correlation between two random variables centered at 0 imply that whenever one variable is negative, so too is the other. Due to this, we focus only on ω as the index. The proof follows identically if replaced by an index on θ.

$$\begin{aligned}\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x} = & \cancel{f_x(x)}\hat{B} + \mathbb{E}[\theta f_x(x)|\omega < \bar{\omega}] + \mathbb{E}[\omega h_x(x)|\omega < \bar{\omega}] - \cancel{c}(x) \\ & - \cancel{f_x(x)}\hat{B} + \mathbb{E}[\theta f_x(x)|\omega > \bar{\omega}] + \mathbb{E}[\omega h_x(x)|\omega > \bar{\omega}] - \cancel{c}(x)\end{aligned} \tag{22}$$

When $h_x(X) > 0$, Equation 22 is always negative. Expected marginal profit is always higher in the good trigger state when shocks are perfectly correlated.

When $h_x(X) < 0$, Equation 22 is ambiguous. The sign of each line depends on the relative effect between $f_x(X)$ and $h_x(X)$. If the risk effects term dominates then Equation 22 will be positive. Without further information it is impossible to know which effect dominates.

A.3 Partial derivatives

Partial derivatives used to sign Equation 14 are shown below. For brevity, $\pi(X, \widehat{B}, \omega, \theta)$ is reduced to π.

$$\frac{\partial U}{\partial x_a \partial x_a} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_a} + u'(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_a x_a}]dz_i \right.$$
$$\left. + \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_a} + u'(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_a x_a}]dz_i \right] dz_r \tag{23}$$

$$\frac{\partial U}{\partial x_b \partial x_b} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_b x_b}]dz_i \right.$$
$$\left. \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_b x_b}]dz_i \right] dz_r \tag{24}$$

$$\frac{\partial U}{\partial x_a \partial x_b} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_a x_b}]dz_i \right.$$
$$\left. \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_a x_b}]dz_i \right] dz_r \tag{25}$$

$$\frac{\partial U}{\partial x_b \partial x_a} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_b x_a}]dz_i \right.$$
$$\left. \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_b x_a}]dz_i \right] dz_r \tag{26}$$

$$\begin{aligned} \frac{\partial U}{\partial x_a \partial \gamma} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)u''(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_a}(1-J(\bar{z}_i)dz_i \right. \\ \left. \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)u''(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_a}(-J(\bar{z}_i))dz_i \right] dz_r \end{aligned} \tag{27}$$

$$\begin{aligned} \frac{\partial U}{\partial x_b \partial \gamma} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{z}_i} j_{\omega,\theta}(\omega,\theta)u''(\pi + (1-J(\bar{z}_i))\gamma)\frac{\partial \pi}{\partial x_b}(1-J(\bar{z}_i)dz_i \right. \\ \left. \int_{\bar{z}_i}^{\infty} j_{\omega,\theta}(\omega,\theta)u''(\pi - J(\bar{z}_i)\gamma)\frac{\partial \pi}{\partial x_b}(-J(\bar{z}_i))dz_i \right] dz_r \end{aligned} \tag{28}$$

A.4 Proof of Proposition 4.1

Proof. Lemma 3.1 allows us to sign the partial equations Equation 27 and Equation 28 for any risk effect on either input. Concave utility by definition leads to $u'' < 0$. For simplicity, we will only focus on $\frac{\partial U}{\partial x_a \partial \gamma}$, but all applies equally to $\frac{\partial U}{\partial x_b \partial \gamma}$. Insurance payouts equalize profits between different states. If insurance completely covers all loss and x_a is risk increasing, then $\frac{\partial U}{\partial x_a \partial \gamma}$ is positive.

$$\begin{aligned}\frac{U}{\partial x_a \partial \gamma} = \int_{-\infty}^{\infty} & \overbrace{j_\theta(\theta) J(\bar{\theta})(1 - J(\bar{\theta})) u''(\theta, \cdot)}^{-} \\ & \left[\underbrace{\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x_a} d\omega - \int_{\bar{\theta}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x_a} d\omega}_{-} \right] d\theta \\ > 0 &\end{aligned} \tag{29}$$

Suppose both inputs are risk increasing so $\frac{\partial U}{\partial x_a \partial \gamma}$ and $\frac{\partial U}{\partial x_b \partial \gamma}$ are positive. The only way for Equation 14 to be unambiguously positive is for $\frac{\partial U}{\partial x_a \partial x_b}$ and $\frac{\partial U}{\partial x_a \partial x_b}$ to be positive.

$$\frac{\partial x_a}{\partial \gamma} = \frac{\overbrace{-1}^{-}}{Det} \left[\overbrace{\overbrace{\frac{\partial U}{\partial x_b \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} - \overbrace{\frac{\partial U}{\partial x_a \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{+}}^{-} \right] > 0$$

$$\frac{\partial x_b}{\partial \gamma} = \frac{\overbrace{-1}^{-}}{Det} \left[\overbrace{\overbrace{\frac{-\partial U}{\partial x_b \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} + \overbrace{\frac{\partial U}{\partial x_a \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{+}}^{-} \right] > 0$$

Both risk increasing inputs will be raised with index insurance. Repeating the same steps above with risk decreasing inputs shows both inputs unambiguously decrease with index insurance.

Now suppose inputs have mixed risk effects. For simplicity, x_a will be risk increasing and x_b will be risk decreasing. The results will hold for the opposite case. By Lemma 3.1, $\frac{\partial U}{\partial x_a \partial \gamma}$ is positive, while $\frac{\partial U}{\partial x_b \partial \gamma}$ is negative. Equation 14 will be unambiguously positive if $\frac{\partial U}{\partial x_a \partial x_b}$ and $\frac{\partial U}{\partial x_b \partial x_a}$ are negative.

$$\frac{\partial x_a}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial U}{\partial x_b \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} - \overbrace{\frac{\partial U}{\partial x_a \partial x_b}}^{+} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{-}}^{-} \right] > 0$$

$$\frac{\partial x_b}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial U}{\partial x_b \partial x_a}}^{+} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} + \overbrace{\frac{\partial U}{\partial x_a \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{-}}^{+} \right] < 0$$

The risk increasing input will be raised with index insurance, while the risk decreasing input will be lowered.

If these conditions do not hold, then it is impossible to determine which additive element outweighs the other, and the insurance effects on optimal input use will be ambiguous regardless of the underlying risk effects of an input.

□

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